ENERGYPLUS: NEW, CAPABLE AND LINKED

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INTRODUCTION

For more than twenty years, the U.S. government supported development of two building energy simulation programs, DOE-2 and BLAST. BLAST (Building System Laboratory 1999), sponsored by the U.S. Department of Defense (DOD), has its origins in the NBSLD program developed at the U.S. National Bureau of Standards (now NIST) in the early 1970s. DOE–2 (Winkelmann et al. 1993), sponsored by the U.S. Department of Energy (DOE), has its origins in the Post Office program written in the late 1960s for the U.S. Post Office. Both programs are widely used throughout the world. The main difference between the programs is load calculation method—DOE–2 uses a room weighting factor approach while BLAST uses a heat balance approach.

Each program comprises hundreds of subroutines working together to simulate heat and mass energy flows throughout a building. In some cases, subroutines in DOE–2 were more accurate. In other cases, subroutines in BLAST were more accurate. In both cases, simulation methodologies were often difficult to trace due to decades of development (and multiple authors). Often, this results in 'spaghetti code' with data and subroutines for a particular simulation capability spread throughout the program. To modify either program, a developer must have many years experience working within the code, knowledge of code unrelated to their task (because of the spaghetti), and (often for sponsors) an extraordinary investment of time and money.

Many people questioned why the U.S. government supported two separate programs with comparable capabilities. Discussions on merging the two programs began in earnest in 1994 with a DOD-sponsored workshop. Although nothing concrete resulted from that workshop, DOE eventually took the initiative and began developing a new program named EnergyPlus in 1996. The EnergyPlus team includes U. S. Army Construction Engineering Research

Laboratories (CERL), University of Illinois (UI), Lawrence Berkeley National Laboratory (LBNL), Oklahoma State University (OSU), GARD Analytics, Florida Solar Energy Center, and DOE. In this paper, we present an overview of the structure of EnergyPlus along with current and planned capabilities.

WHAT IS ENERGYPLUS?

EnergyPlus comprises completely new, modular, structured code based on the most popular features and capabilities of BLAST and DOE-2. It is primarily a simulation engine—we did not develop a user-friendly graphical interface. Input and output are simple comma-separated, ASCII text files, much simpler input than either DOE–2 or BLAST. Figure 1 shows screen images of EnergyPlus utilities and example results. Both BLAST and DOE–2 have successfully attracted third-party developers to create user interfaces and new modules. During development of Version 1.0, we invited these same developers to work with the development team on new simulation modules or to develop their own user interfaces.

One of the main goals we set for developing EnergyPlus was to create a well-organized, modular structure to facilitate adding features and links to other programs. To support such a modular structure, we selected Fortran 90 as our programming language for EnergyPlus because of its modern, modular, object-based structure, and to allow us some backward compatibility during the development process.

ENERGYPLUS STRUCTURE

In two workshops on next generation energy tools sponsored by DOE (Crawley et al. 1997), there was strong consensus that a more flexible and robust tool with additional capabilities is needed. One of the highest priorities was an integrated (simultaneous loads and systems) simulation for accurate temperature and comfort prediction. In response to these findings, we decided that integrated simulation should be the underlying concept for EnergyPlus. Loads calculated (by a heat balance engine) at a user-specified time step (15-minute default) are passed to the building systems simulation module at the same time step. The building systems simulation module, with a variable time step (down to seconds as needed), calculates heating and cooling system and plant and electrical system response. Feedback from the building systems simulation module on loads not met is reflected in the next time step of the load calculations in adjusted space temperatures if necessary.

By using an integrated solution technique in EnergyPlus, the most serious deficiency of BLAST and DOE–2—inaccurate space temperature predication due to no feedback from the HVAC module to the loads calculations—is solved. Accurate prediction of space temperatures is crucial to energy efficient system engineering—system size, plant size, occupant comfort and occupant health are dependent on space temperatures.

Integrated simulation also allows users to evaluate a number of processes that neither BLAST nor DOE–2 can simulate well. Some of the more important include:

- Realistic system controls
- Moisture adsorption and desorption in building elements
- Radiant heating and cooling systems
- Interzone air flow

Figure 2 shows the overall program structure. EnergyPlus has three basic components—a simulation manager, a heat and mass balance simulation module, and a building systems simulation module. The simulation manager controls the entire simulation process. The heat balance calculations are based on IBLAST—a research version of BLAST with integrated HVAC systems and building loads simulation.
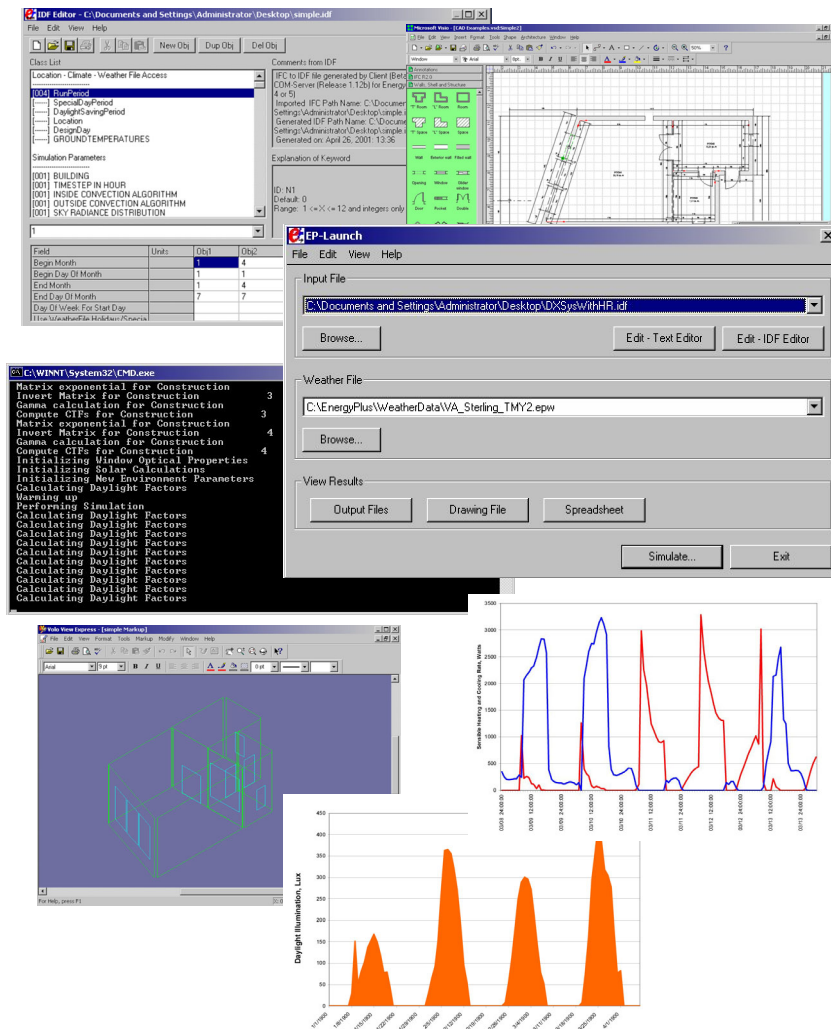
Figure 1. Screen Images of EnergyPlus Utilities and Results

A new building systems simulation manager handles communication between the heat balance engine and various HVAC modules and loops, such as coils, boilers, chillers, pumps, fans, and other equipment/components. (In the first release, the building systems simulation manager only has HVAC systems and equipment/components. Future releases of EnergyPlus will include electrical systems simulation.)   Gone are the hardwired 'template' systems (VAV, Constant Volume Reheat, etc.) of DOE–2 and BLAST—replaced by user-configurable heating and cooling equipment components formerly within the template. This gives users much more flexibility in matching their simulation to the actual system configurations. The building systems simulation module also manages data communication between the HVAC modules, input data, and output data structures. The simulation manager, heat balance simulation manager, and building systems simulation manager are described in more detail below.

SIMULATION MANAGEMENT
At the outermost program level, the Simulation Manager controls the interactions between all simulation loops from a sub-hour level up through the user selected time step and simulation period—whether day, month, season, year or several years. Actions of individual simulation modules are directed by the simulation manager, instructing simulation modules to take actions such as initialize, simulate, record keep, or report.

We created the simulation manager to specifically address the legacy issues of spaghetti code and lack of structure in DOE-2 and BLAST. The simulation manager provides several critical benefits:

- major simulation loops are contained in a single module
- modules are self-contained and more object-based
- data access is controlled
- new modules can be easily added

HEAT AND MASS BALANCE

As noted earlier, the underlying building thermal zone calculation method in EnergyPlus is a heat balance model. The fundamental assumption of heat balance models is that air in each thermal zone can be modeled as well stirred with uniform temperature throughout, which does not reflect physical reality well. The only current alternative is Computational Fluid Dynamics (CFD)—a complex and computationally intensive simulation of fluid (in this case, air) movement. Currently, CFD is most useful in research applications. Several groups are working on models somewhere between the well-stirred model and a full CFD calculation. The modular structure of EnergyPlus allows these new models to be included in future releases as they become available. The other major assumption in heat balance models is that room surfaces (walls, windows, ceilings, and floors) have:

- uniform surface temperatures,
- uniform long- and short-wave irradiation,
- diffuse radiating surfaces, and
- one-dimensional heat conduction.

The integrated solution manager manages the surface and air heat balance modules and acts as an interface between the heat balance and the building systems simulation manager. The surface heat balance module simulates inside and outside surface heat balance; interconnections between
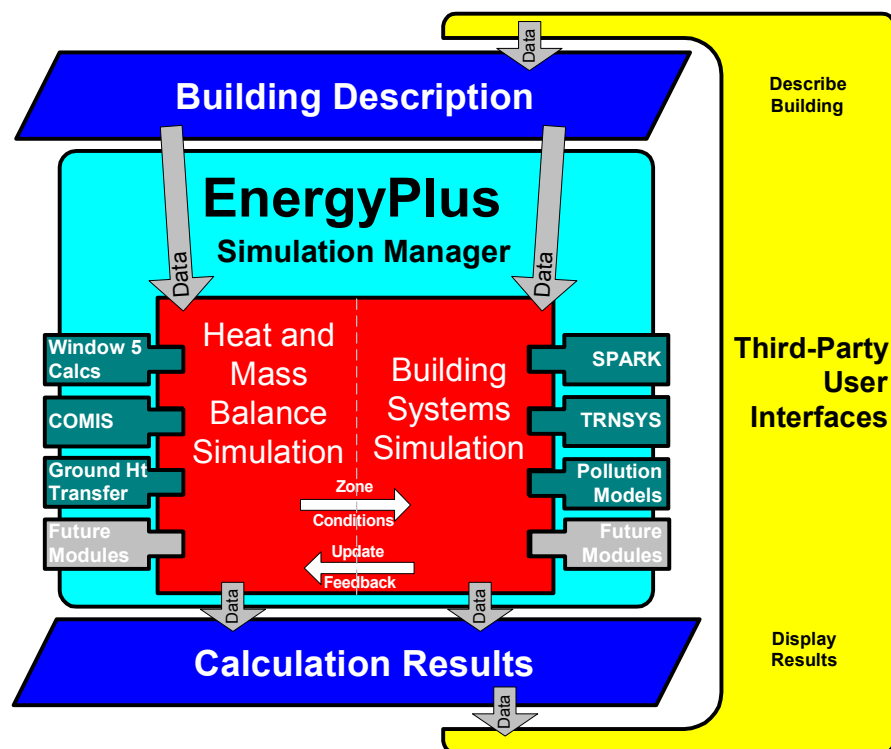
Figure 2. Overall EnergyPlus Structure

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heat balances and boundary conditions; and conduction, convection, radiation, and mass transfer (water vapor) effects. The air mass balance module deals with various mass streams such as ventilation and exhaust air, and infiltration. It accounts for thermal mass of zone air and evaluates direct convective heat gains. Through this module we have connected to COMIS (Huang et al. 1999) for improved multizone airflow, infiltration, indoor contaminant, and ventilation calculations.

In addition to the basic heat and mass balance engine from IBLAST, we created three new modules based on capabilities within DOE–2: daylighting illumination, WINDOW 5-based fenestration, and anisotropic sky. The daylighting module calculates interior daylight illuminance, glare from windows, glare control, and electric lighting controls (on/off, stepped, continuous dimming), and calculates electric lighting reduction for the heat balance module. In the future, the daylighting module will include an improved interior interreflection calculation, reflection from neighboring buildings, and handling of complex fenestration systems (such as blinds, light shelves, roof monitors). The fenestration module includes capabilities from WINDOW 5—accurate angular dependence of transmission and absorption for both solar and visible radiation, and temperature-dependent U-value. Users can enter a layer-by-layer window description or choose windows from the library (such as conventional, reflective, gas fill, low-e, and electrochromic windows. For sun control, movable interior and exterior window shades and blinds and electrochromic glazing can be simulated. The WINDOW 5 algorithms now also include coatings and framing elements. The sky model includes non-isotropic radiance and luminance distribution throughout the sky based on an empirical model (Perez et al. 1991, 1990) as a function of sun position and cloud cover. This non-uniform radiance distribution improves calculation of diffuse solar on tilted surfaces (walls and sloped roofs). More information on the window calculations within EnergyPlus are provided by Winkelmann (2001).

Several other modules have been reengineered for inclusion in EnergyPlus: solar shading from BLAST and conduction transfer function calculations from IBLAST. The major enhancements of the IBLAST (and EnergyPlus) heat balance engine over BLAST include mass transfer and radiant heating and cooling. The mass transfer capability within EnergyPlus allows fundamental, layer-by-layer solution for mass transfer through surfaces and a mass balance on zone air similar to the air heat balance. The radiant heating and cooling models are an expansion of the conduction transfer function and incorporate thermal comfort calculations. This provides a means for improved modeling and control capabilities for the new building systems simulation manager.

One last important feature of the EnergyPlus heat balance engine is that it is essentially identical in functionality to the Loads Toolkit completed in 2001 by UI under ASHRAE Research Project 987 (987-RP). UI developed both the Loads Toolkit and the EnergyPlus heat and mass balance engine and used the programming standard developed in the EnergyPlus project to produce the Loads Toolkit (Pedersen et al. 2001). Both projects benefited: modularization efforts started by EnergyPlus were useful in the Loads Toolkit and new component models developed for the Loads Toolkit enhanced EnergyPlus. Strand et al (2001) provide more information on the heat and mass balance implementation in EnergyPlus in comparison with the ASHRAE Loads Toolkit.

BUILDING SYSTEMS SIMULATION MANAGER
After the heat balance manager completes simulation for a time step, it calls the Building Systems Simulation Manager, which controls the simulation of HVAC and electrical systems, equipment and components and updates the zone-air conditions. EnergyPlus does not use a sequential simulation method (first building loads, then air distribution system, and then central plant) as found in DOE–2 and BLAST since this imposes rigid boundaries on program structures and limits input flexibility. Instead, we designed the building systems simulation manager with several objectives in mind:

- fully integrated simulation of loads, systems, and plant
- modular
- extensible

Integrated simulation models capacity limits more realistically and tightly couples the air and water side of the system and plant. Modularity is maintained at both the component and system level. This simplifies adding new components and flexibly modeling system configurations and, at the system level, equipment and systems are connected clearly to zone models in the heat balance manager. To implement these concepts, we use loops throughout the building systems simulation manager—primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings and eventually will simulate head and thermal losses that occur as fluid moves in each loop. As mentioned earlier, EnergyPlus has no hardwired 'template' systems. Instead, we have developed equivalent input file templates for the each of the most popular system types. These templates provide an easy starting point for users to develop inputs for system configurations that differ from 'default' configurations. The air loop simulates: air transport, conditioning and mixing, and includes supply and return fans, central heating and cooling coils, heat recovery, and controls for supply air temperature and outside air economizer. The air loop connects to the zone through the zone equipment. Zone equipment includes diffusers, reheat/recool coils, supply air control (mixing dampers, fan-powered VAV box, induction unit, VAV dampers), local convection units (window air-conditioner, fan coil, water-to-air heat pump, air-to-air heat pump), high-temperature radiant/convective units (baseboard, radiators) and low-temperature radiant panels. More than one equipment type can be specified for a zone—something neither DOE-2 nor BLAST could do. However, users must specify equipment in the order it will be used to meet zone heating and cooling demand.

For the air loop, the solution method is iterative, not 'single-pass' as in DOE–2 and BLAST. In order to specify equipment connections to a loop, nodes are defined at key locations around the loop with each node assigned a unique numeric identifier. Node identifiers store loop state variables and set-point information for that location in the loop. We use an iterative solution technique to solve for unknown state variables along with control equation representations. These representations connect the set points at one node with the control function of a component, such as fan damper position and cooling coil water flow rate. In this schema, all the loop components are simulated first, and then the control equations are updated using explicit finite difference. This procedure continues until the simulation converges. Typical control schemes are included in the input file templates described earlier.

There are two loops for HVAC plant equipment—a primary loop (for supply equipment such as boilers, chillers, thermal storage, and heat pumps) and a secondary loop (for heat rejection equipment such as cooling towers and condensers). Equipment on the primary plant loop is specified by type (gas-fired boiler, open drive centrifugal chiller) and its operating characteristics. In the first release of EnergyPlus, we include performance-based equipment models (such as in BLAST and DOE–2), but because of the modular code, it will be easy for developers to add other types of models in future releases. As in the air loop, the primary and secondary plant loops use explicit nodes to connect equipment to each loop. Connections between the air loop and zone equipment and the primary and secondary loops are made through the node data structure and must be explicitly defined in the input file. Fisher et al. (1999) provide additional information about the modular, loop-based approach to building systems simulation in EnergyPlus. A similar loop approach is proposed for a new electrical loop for simulating electrical systems—supply (utility, photovoltaic modules, and fuel cells), demand (plug loads, lighting, and other electrical loads), and measurement (meters).

In the longer term, EnergyPlus users will have more systems and equipment options through a link to SPARK (Buhl et al. 1993), an equation-based simulation tool. SPARK is a better solver for complex iterative problems. SPARK already has a library of HVAC components based on the ASHRAE primary and secondary toolkits (LeBrun et al. 1999, Brandemuehl et al. 1993).

EnergyPlus will continue to have system types (in input file templates) but developers and advanced users will be able to easily build complex new HVAC models with SPARK. A similar link to the TRNSYS simulation model (Solar Energy Laboratory 2001) provides users with photovoltaic simulation capabilities.

INPUT, OUTPUT, AND WEATHER DATA

Both DOE–2 and BLAST have highly-structured but user readable input files that have evolved over many years. Instead of user readability, we designed the EnergyPlus input files for easy maintenance and expansion. We chose to keep the input file simple so that input data could be translated easily from CAD systems, other building-related programs, and pre-processors similar to those written for BLAST and DOE–2. EnergyPlus input files are somewhat readable but can be cryptic and were not intended to be the main interface for typical end-users. We expect most users will use an interface for EnergyPlus from a third-party developer. To make it easy for current DOE–2 and BLAST users to move to EnergyPlus, the team has written utilities that convert BLAST and DOE–2 loads input to the new EnergyPlus input structure.

The International Alliance for Interoperability has been developing an object-oriented data protocol for building information exchange (Bazjanac and Crawley 1999). Initial implementations of the Industry Foundation Classes (IFC) began appearing in building CAD programs in 2001. With the first release of EnergyPlus, we provided a utility for creating EnergyPlus input files from IFC files. Note that version 2.0 of the IFC only includes geometry information—additional building information including HVAC systems and equipment will available in future updates to the IFC (2.x, 3.0).

EnergyPlus uses a free format input file that contains a complete object-based description of the building and its systems. The basic syntax is:

object, data, data, data, . . ., data;

'Object' is a pre-defined word denoting a building component, such as SURFACE, MATERIAL, LIGHTING, SYSTEM, HEATING COIL, and BOILER. This word is followed by a list of data values and terminates with a semicolon. These data describe performance characteristics and intended use for that object in the simulation.

Unlike BLAST and DOE–2, input files must explicitly provide all information—there are few default assumptions. Users may include comments throughout their input data file. Rather than have a fixed input file syntax, EnergyPlus reads an input data dictionary at runtime to determine the syntax of the input data file. The general syntax of the input data dictionary is:

Object, A1 [an alpha], N1 [a number],..

For example, (a subset of) the data dictionary for the Location command is:

Location, A1 \field LocationName, N1 \field Latitude, N2 \field Longitude, N3 \field TimeZone, N4 \field Elevation;

For the Location object, this tells the input processor to expect one text field (A1) with the location name followed by four numeric inputs (N1, N2, N3, and N4): latitude, longitude, time zone and elevation, respectively. Following the \ can be variable names, units, defaults (if any) and allowable range of values.

During simulation, EnergyPlus saves results for each time step which can be reported at each time step or aggregated to longer time intervals. This structure and subsequent output uses a similar philosophy to the input—simple text files with a syntax of object, time stamp, data, data, data, . . ., data; . Several report types are available—standard output (user specified variables at specified time intervals), one time output (such as input echo, input verification and interim calculations), and visual surface output (including DXF outputs). Because the data structure is simple and comma-separated, output post-processors can easily read the data and create more

elaborate reports. One drawback of our simple file format is that the output files can become very large.

The other major data input is weather. Rather than a binary file created by a separate weather processor, again we use a simple text-based format, similar to the input data and output data files. The weather data format includes basic location information in the first eight lines: location (name, state/province/region, country), data source, latitude, longitude, time zone, elevation, peak heating and cooling design conditions, holidays, daylight savings period, typical and extreme periods, two comment lines, and period covered by the data. The data are also comma-separated and contain much of the same data in the TMY2 weather data set (National Renewable Energy Laboratory 1995). EnergyPlus does not require a full year (8760 or 8784 hours) of data for its weather files. In fact, EnergyPlus allows and reads subsets of years and even sub-hourly (5 minute, 15 minute) data—the weather format includes a 'minutes' field. EnergyPlus comes with a utility that reads standard weather service file types such as TD1440 and DATSAV2 and newer 'typical year' weather files such as TMY2, IWEC, and WYEC2. More information on the weather data format is contained in Crawley, Hand and Lawrie (1999).

Weather data in the EnergyPlus weather format for more than 560 locations are available for download from the EnergyPlus web site—275 locations in the United States, 55 locations in Canada, and more than 230 other locations in 70 countries.

In summary, all the data files associated with EnergyPlus—input, output, and weather—have simple self-contained formats that can be easily read and interpreted by programs such as spreadsheets, databases, or custom user interface programs.

TESTING

A critical part of EnergyPlus development has been continuous testing using several simultaneous paths. The primary emphasis to date has been on comparative and analytical testing. Comparative testing of basic loads algorithms has been completed using ASHRAE Standard 140-2001 (ASHRAE 2001) series of tests, which consist of a basic shoebox with windows and shading for both low mass and high mass construction. Figure 3 shows sample EnergyPlus results compared against reference data for a number of other simulation programs provided with Standard 140. Comparative version testing of EnergyPlus against itself has been extremely useful in detecting and resolving problems introduced during development. The testing to date demonstrates that EnergyPlus provides results in good agreement with other simulation programs for simple cases. We will continue to aggressively test EnergyPlus throughout future development. As testing results are completed, the results and methodologies will become available on the EnergyPlus web site. For more information on the testing and validation of EnergyPlus, see Witte et al. (2001).

BEYOND RELEASE 1.0

The first release of EnergyPlus (Version 1.0.0) was released in April 2001, followed by incremental releases in June 2001 and April and July 2002. We plan to release the next major version of EnergyPlus (1.1) in 2003 with subsequent updates annually. The major focus for the next major releases includes extensive ventilation improvements, electrical system simulation, generalized surface polygons and under floor air distribution (stratified zones).

SUMMARY

EnergyPlus is a new building energy simulation program that combines the best features of the BLAST and DOE–2 programs along with many new capabilities. Connectivity and extensibility to facilitate third party interface and module development were overall objectives throughout development. EnergyPlus not only combines the best features of the BLAST and DOE–2 programs, but also represents a significant step forward in terms of computational techniques and program structures. We released EnergyPlus Version 1.0.0 in April 2001 and plan to release updates on a regular annual schedule. In mid-2002, we began planning new features to include in the next several versions based on suggestions by users, developers, and the team. Working with

ASHRAE 140 Comparison (Denver, dry/cold)
Low Mass Building Annual Cooling
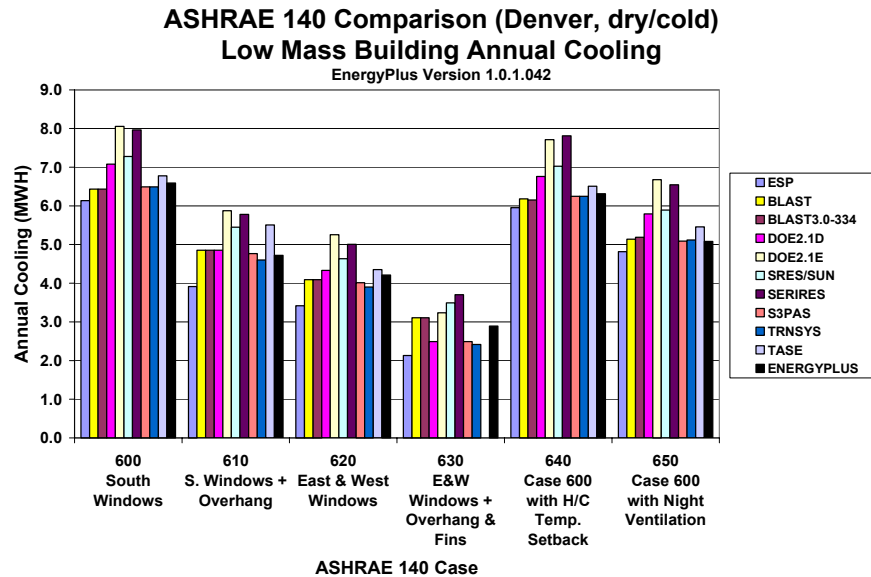EnergyPlus Version 1.0.1.042

Figure 3. Sample EnergyPlus Comparative Testing Results

a coordinating group of users and developers, we have selected the features and capabilities for that release. New features already under development are electrical system simulation, fuel cells, microturbines, advanced fenestration and daylighting, and other building technologies. Many of these features will be included in the second major release (1.1) currently planned for April 2003.

WEB RESOURCES
Information on EnergyPlus, including schedule, availability of new releases, documentation, weather data for more than 560 locations worldwide, licensing, programming standards, and other documentation:

> http://www.energyplus.gov

Web-based directory of more than 240 building-related software tools from around the world:

> http://www.energytoolsdirectory.gov

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